Altitude-Controlled Balloon Concepts for Venus and Titan

Energy, Mass and Stability Tradeoffs

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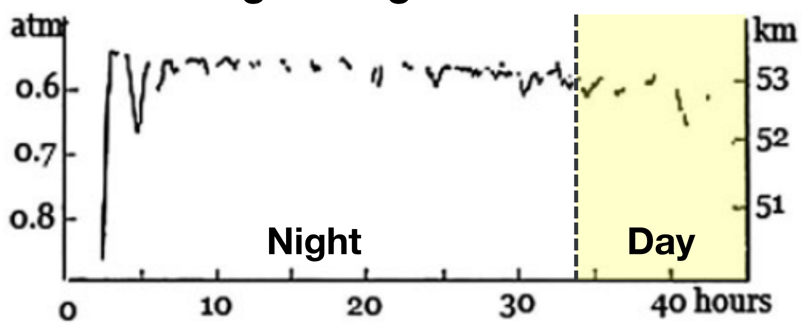
Motivation – Balloons at Venus

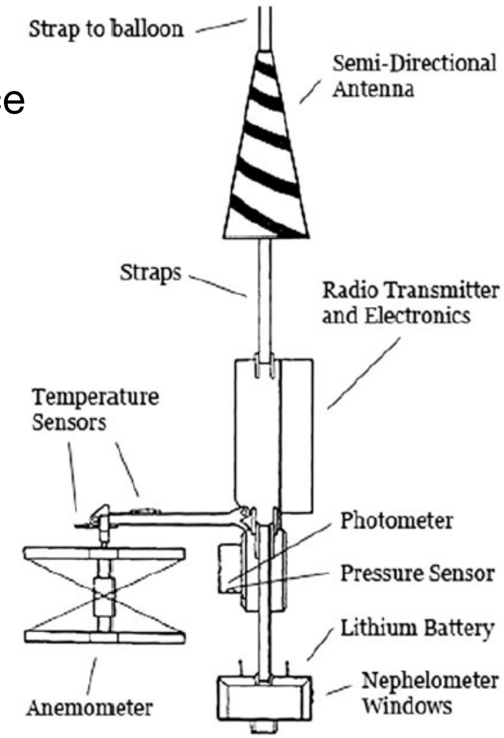
Science driver: **global-scale mobility** and **in-situ measurements**

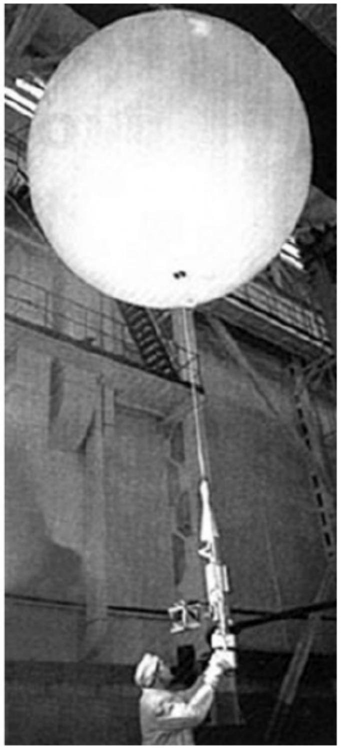
- Vega 1 & 2 (1985) demonstrated concept with small payload
  - 3.4m diameter balloon, 6kg gondola
  - 50hr battery design life
  - Flew one third of Venus circumference
- More recent proposals (VEVA, VALOR) aimed for larger scale

Vega 1 Flight Altitude



[Mitchell, via Huntress & Marov 2011]



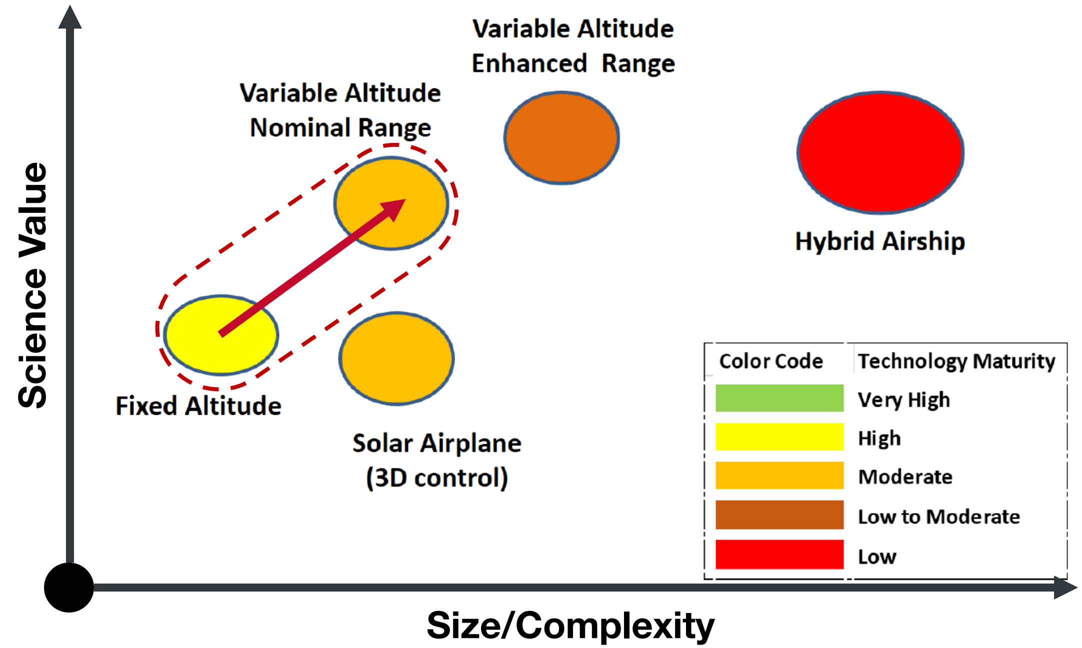


Superpressure balloons have been demonstrated on Venus, showing altitude stability and in-situ capability

Venus Aerial Platforms Study

Venus Aerial Platform Concepts

VEXAG Science Goal Ranking



[Venus Aerial Platforms Study Team 2018]
NASA Funded - involvement of GSFC, JPL, LaRC, Glenn, Ames, SwRI (and many more, both industry & academic)

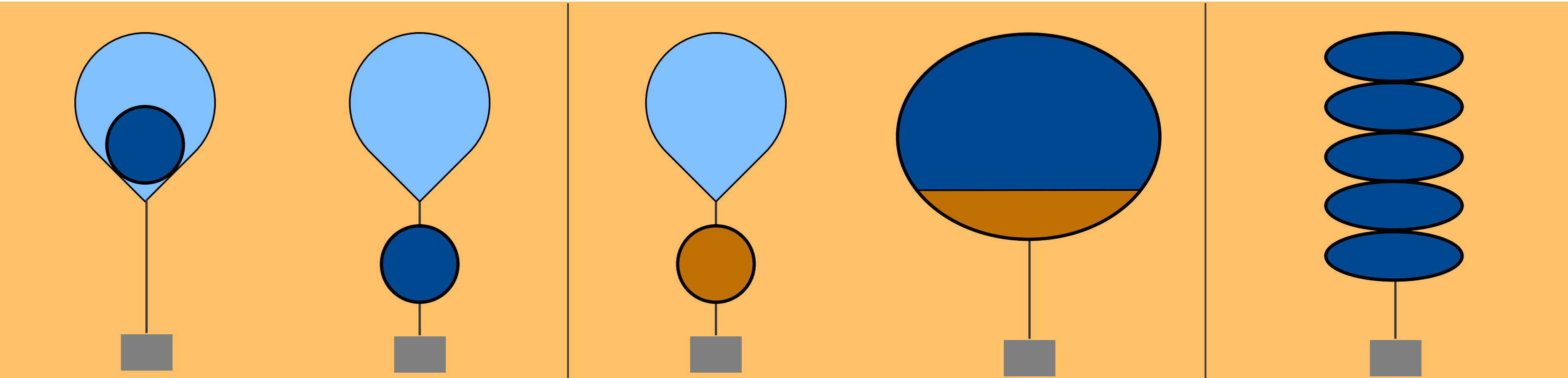
Variable Altitude Advantages:

- Get to sample "different air" as vary in altitude and latitude
  - Cloud chemistry, lightning, greenhouse physics, biologically relevant chemistry
- Some control of ground-track due to wind shear (Venus), full station keeping possible on Titan [Blackmore 2010]

Variable altitude balloons increase science return for a moderate increase in size/complexity

Types of Variable Altitude Balloons

Pumped Helium (PH)		Air Ballast (AB)		Mechanical Compression (MC)



Helium superpressure balloon **inside** of helium zeropressure balloon [1]	Helium superpressure balloon **outside** of helium zeropressure balloon	Air superpressure balloon **outside** helium zeropressure balloon [2]	Single superpressure balloon with **internal membrane** separating helium and air [3]	**Stack of connected** superpressure helium balloons [4]
Change volume by pumping into SP balloon		**Change weight** by pumping air into SP balloon		**Change volume** by squeezing

All of these balloon types can actively control altitude, but with key differences:

- A large volume of superpressure gas is more altitude-stable (i.e. a sky-anchor)
- Superpressure envelope material is necessarily heavier
- Venus gas is corrosive, so Teflon must be added to inside of envelopes if air is internal

Unpressurized Helium

Pressurized Helium

Air

Pressurized Air

[1] Voss 2009 [2] World View 2019 [3] Loon LLC 2019 [4] de Jong 2017

Study Goals and Method

Goal: Compare different balloon types for a **common set of requirements**

Functional Requirements:

- **Long-lived aerial platform:** capable of flights over a year
- **Fly with multiple-altitude capacity:** 52-62km on Venus, 1-11km on Titan
- **Actively control altitude**: allows north/south control on Venus and perhaps station keeping on Titan
- **Carry flagship-class payload gondola:** 100kg Venus, 200kg Titan (RTG)
- **Fly in both day and night:** solar heating increases pressure and/or volume
- **Tolerate vertical wind gusts:** 3m/s on Venus, 0.5m/s on Titan, to an acceptable altitude excursion (no balloon bursting, grounding, or overheating)

Methodology

Methodology:

(1) Solve balloon design that satisfies low-altitude equilibrium

(2) Find smallest superpressure needed to rejects low altitude disturbance

(3) Predict pump/squeezing action for entire altitude range

(4) Determine peak pressure due to pump/squeeze and solar flux

(5) Increase envelope weight for pressure load, and iterate (1-5)

Assumptions

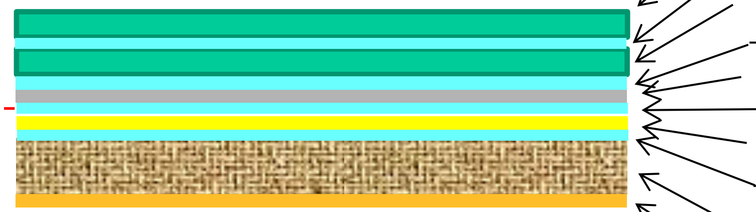
- **Low altitude margin:** 1kPa margin after downdraft to avoid loss of stability
- **Strength margin:** envelope mass increased 20% for seams, extra 30% for loads
- **Ideal gases:** both atmosphere and internal helium gas
- **Solar heating**: linear scaling with altitude
- **Drag coefficients**: 0.5 (separated flow) for all large balloons, 0.25 for secondary balloons if in wake
- **Atmospheric data:** Venus atmosphere of 97% CO_2, 3% N_2, and VIRA P&T properties [Seiff et. al. 1985]. Titan atmosphere of 5% CH_4, 95% N_2 with P&T from Huygens data [Niemann et. al. 2010]

Converged set of designs described in next slides

Envelope Weight (Venus)

Materials

Total laminate areal density = 217 g/m^2



[Hall et al. 2008]

Envelopes

Acidic Air / Pressurized Helium	Acidic Air / Unpressurized Helium	Unpressurized Helium / Pressurized Helium	Acidic Air / Pressurized Acidic Air
~270 g/m^2 (Hall 2008, plus margin)	**~170 g/m^2 (No Vectran)**	**~120 g/m^2 (No Teflon)**	**~330 g/m^2 (Teflon both sides)**

Balloons

	Pumped Helium (balloon in balloon)	Pumped Helium (two balloon)	Air Ballast (two balloon)	Air Ballast (One balloon)	Mech. Compression (segment balloon)
Superpressure Diameter [m]	5.30	5.2	6.93	11.8	10.5
Zeropressure Diameter [m]	10.6	10.4	12.6	None	None
Total Mass [kg] of envelopes & payload	189.5	199.4	271.0	335.4	245.9

Acid resistance and superpressure add weight, which require a larger balloon

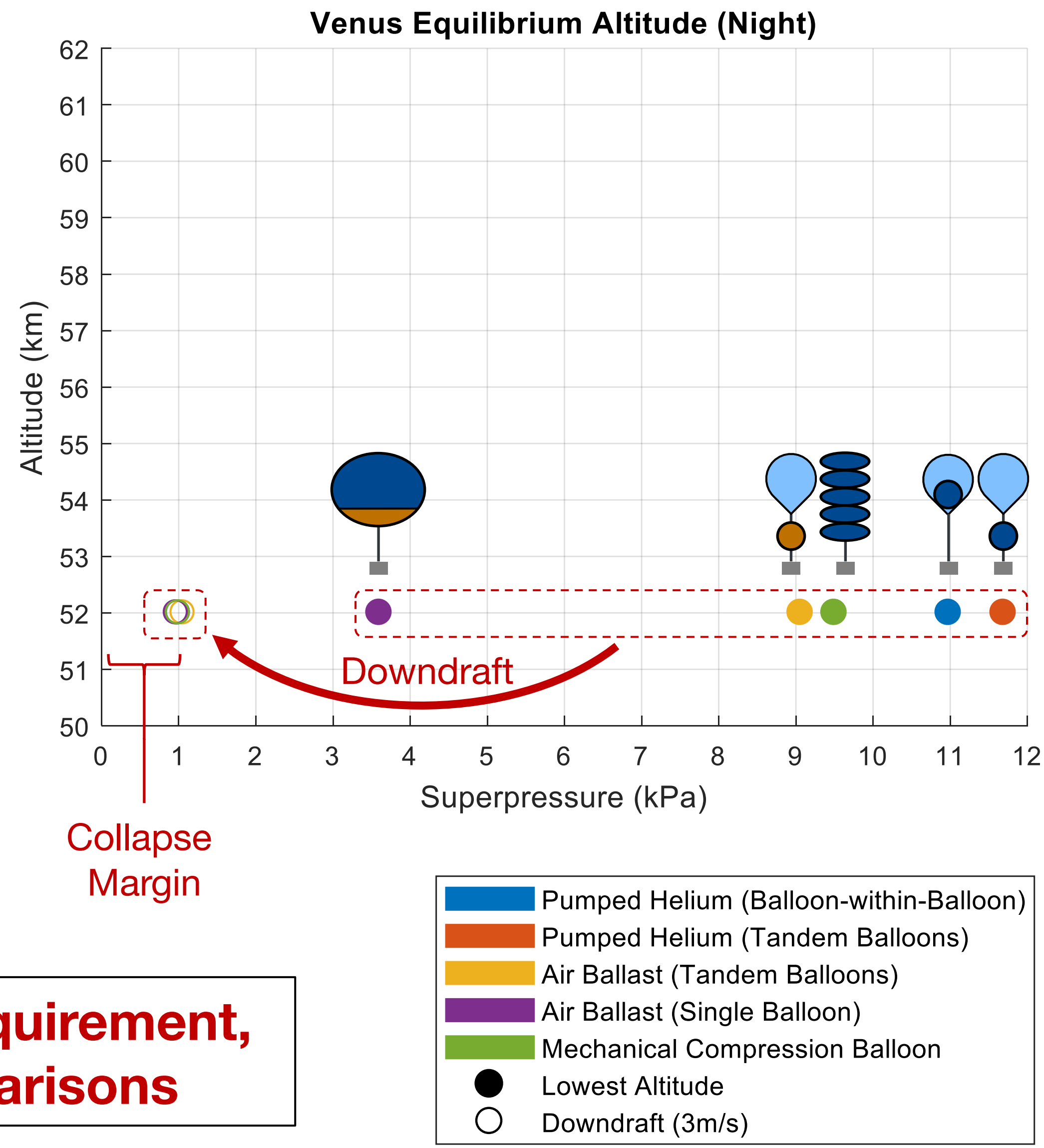
Low Altitude Analysis (Venus)

Downdraft effects:

- **Best if passively mitigated.** Downdrafts are fast and can happen at night (less power available)
- **Model: Balloons vent pressure** to maintain altitude, but **only to 1kPa**

Results

- **Defining margin of 1kPa** narrows design space to one solution per balloon type
- **Single Air Ballast Balloon needs the smallest excess superpressure** as it has a large restorative volume
- **Other concepts must have significantly higher margin**



All designs can meet requirement, allowing direct comparisons

Mid-Altitude Analysis (Venus)

Altitude effects:

- Both internal and external pressures change with altitude
- Simple relations describe difference over envelope

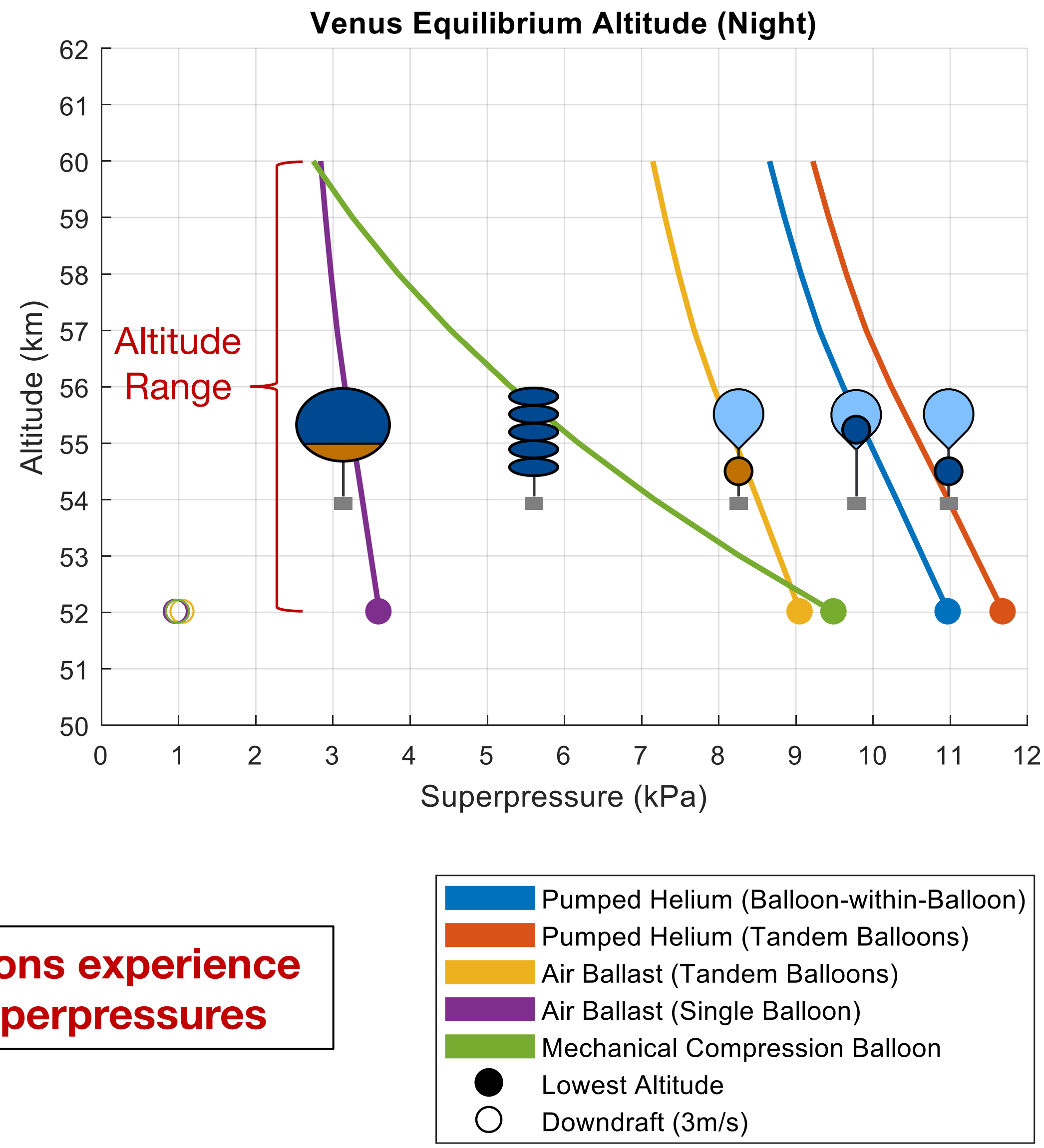
Mechanical Compression:

$$\Delta P(z) \propto P_{\mathrm{atm}}(z)$$

Pumped Helium or Air Ballast:

$$\Delta P(z) \propto T_{\mathrm{atm}}(z)$$

- Pressure varies more than temperature
- Constant of proportionality depends on gas volumes



Mechanical compression balloons experience a wider range of nighttime superpressures

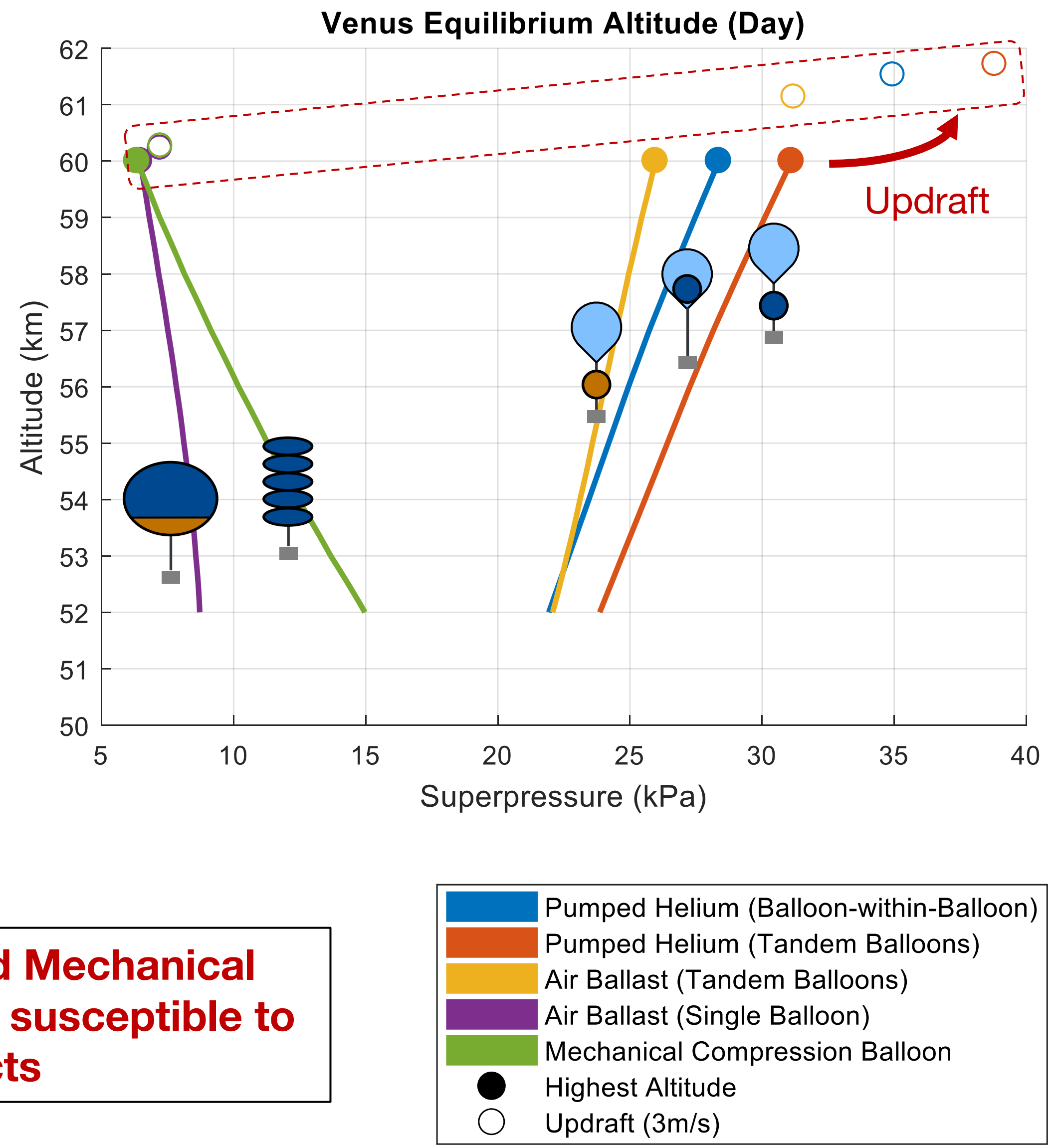
Solar Flux Analysis (Venus)

Solar Heating:

- Rough linear temperature model (+20°C at 52km, further +2°C/km)
- Small volumes of gas pressurize more given the same temperature change
- Increases in superpressure by ~3x, especially at high altitudes.

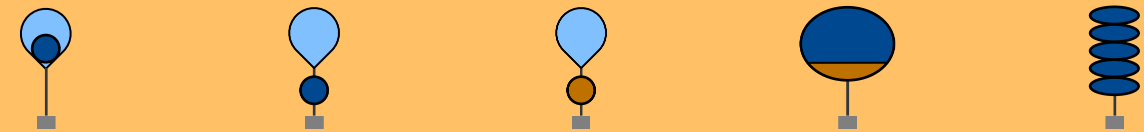
Balloon Implications:

- Two-chamber balloons will necessarily have large daytime superpressures
- Updrafts affect the two-camber balloons more as well



Single-balloon Air Ballast and Mechanical Compression balloons are less susceptible to solar heating effects

Final Mass and Power (Venus)



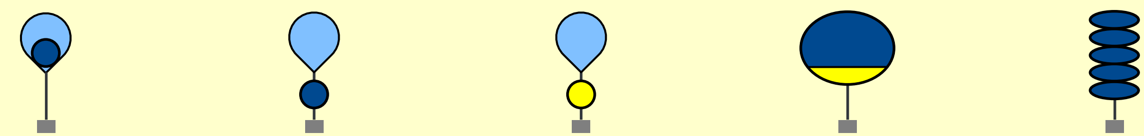
	PH (balloon in balloon)	PH (two balloon)	AB (two balloon)	AB (one balloon)	MC (one balloon)
Converged Design					
ZP balloon areal density (g/m²)	120	120	120	120	N/A
SP balloon areal density (g/m²)	170	270	330	285	270
Zero-P (ZP) balloon diameter	10.6	10.4	12.6	N/A	N/A
Superpressure (SP) balloon diameter	5.30	5.2	6.93	11.8	10.5
Total Envelope mass	89.5	99.4	171.0	235.4	145.9
Minimum superpressure (Pa)	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**
Total Helium mass	20.6	21.6	29.9	38.9	26.8
Performance					
Total aerobot mass (w/o helium)	**189.5**	**199.4**	**271.0**	**335.4**	**245.9**
Maximum superpressure (Pa)	**32,800**	**36,300**	**31,300**	**8,700**	**10,800**
Maximum perturbed altitude (km)	**62.0**	**62.1**	**61.8**	**60.3**	**60.3**
Daylight energy for max to min altitude (J)	**1,270,000**	**1,264,000**	**2,843,000**	**6,282,000**	**2,660,000**

Table Coloring

Lowest Value	Over 25% increase	Over 50% increase	Over 100% increase

Pumped Helium is lightest and uses least power.
Mechanical Compression is more stable and lower superpressure.

Final Mass and Power (Titan)



	PH (balloon in balloon)	PH (two balloon)	AB (two balloon)	AB (one balloon)	MC (one balloon)
Converged Design					
ZP balloon areal density (g/m²)	75	75	75	75	N/A
SP balloon areal density (g/m²)	140	140	160	120	140
Zero-P (ZP) balloon diameter	5.6	4.2	5.6	N/A	N/A
Superpressure (SP) balloon diameter	4.5	4.4	5.0	5.5	5.5
Total Envelope mass	25.3	19.8	31.1	23.3	20.8
Minimum superpressure (Pa)	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**
Total Helium mass	39.5	38.4	41.0	39.6	38.7
Performance					
Total aerobot mass (w/o helium)	**225.3**	**219.8**	**231.1**	**223.3**	**220.8**
Maximum superpressure (Pa)	**6,700**	**6,200**	**7,600**	**4,400**	**4,600**
Maximum perturbed altitude (km)	**11.7**	**11.3**	**11.3**	**11.2**	**11.2**
Daylight energy for max to min altitude (J)	**93,600**	**82,800**	**136,300**	**113,700**	**93,900**

Titan Parameters:

- 1 to 11km altitude
- Add 1°C in daylight
- Vertical wind 0.5 m/s
- 75 g/m² zero-pressure material [Hall et. al. 2008]
- 120 to 160 g/m² superpressure material
- 200kg payload

Titan designs have fewer distinctions in performance (due to lower gravity). However, roughly twice the helium is required compared to Venus.

Conclusions

Essential Physics

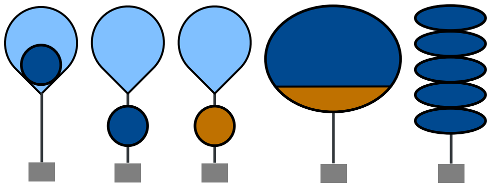
- **Downdrafts** act as limiting requirement that determines the design space
- Most balloons (except M. Comp.) follow **temperature dependence** for loading
- **Large pressurized volumes add altitude-stability** in both wind and sun, but require more power to control
- **Large pressurized volumes are also less loaded** by both wind and sun

Venus vs Titan

- **Envelope weights** are generally higher for Venus, due to acid resistance
- **Helium mass** is higher for Titan, due to atmospheric gas
- **Concepts are stronger differentiated on Venus** in both mass and power

Concept Tradeoffs

- **Pumped helium** has least mass and power
- **Mechanical Compression** is more stable and lower loads
- **Air Ballast** is heavily penalized by Teflon mass on Venus, but may be tenable for Titan



For more detailed analysis (dynamics, solar flux, thermal model, etc.) and DARTS simulation see:
[submitted] Jeffery L. Hall, Jonathan M. Cameron, Michael T. Pauken, Jacob S. Izraelevitz, Mitchell W. Dominguez, Kristopher T. Wehage. Altitude-Controlled Light Gas Balloons for Venus and Titan Exploration. **AIAA Aviation Forum and Exposition, June 2019**

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Backup Slides

Superpressure Relationship Derivation

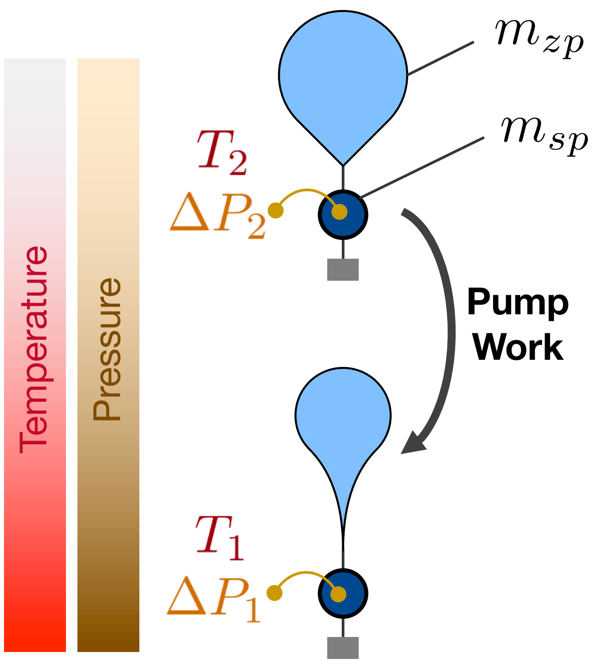
Equilibrium: $B_1 = B_2$

Ideal Gas, Zero ΔT over skin: $\frac{m_{zp,1} R_{he}}{R_a} + \frac{P_1}{R_a T_1} V_{sp} = \frac{m_{zp,2} R_{he}}{R_a} + \frac{P_2}{R_a T_2} V_{sp}$

Mass Flux (ZP Balloon): $m_{zp,2} - m_{zp,1} = \left(\frac{P_1}{T_1} - \frac{P_2}{T_2} \right) \frac{V_{sp}}{R_{he}}$

Mass Flux (SP Balloon): $m_{sp,2} - m_{sp,1} = \frac{(P_2 + \Delta P_2) V_{sp}}{R_{he} T_2} - \frac{(P_1 + \Delta P_1) V_{sp}}{R_{he} T_1}$

Algebraic Manipulation: $\frac{\Delta P_2}{T_2} = \frac{\Delta P_1}{T_1}$



$$\Delta P \propto T$$

Superpressure relationship is a result of ideal gas law, nighttime operation, mass conservation, and buoyancy equilibria

Pump and Cable Energy Expenditures

Work Types

- **Pump Work** from flow of helium over pressure difference
- **Cable Work (PdV)** from compression of helium

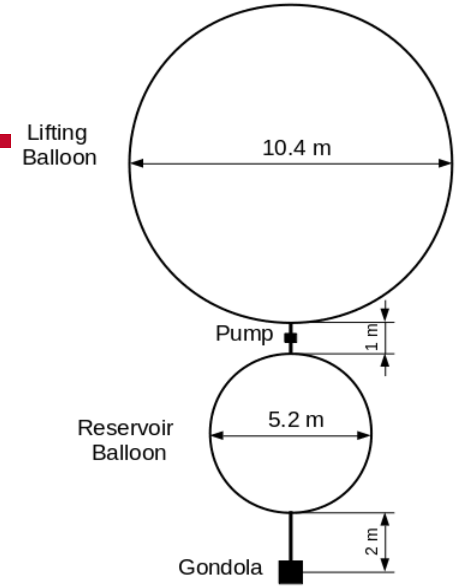
$$\Delta E_{\text{pump}} = \int_{t_i}^{t_f} \dot{W}_{\text{pump}} dt = \int_{t_i}^{t_f} \dot{m}_{\text{gas}} (h_{\text{in}} - h_{\text{in}}) dt$$ (Enthalpy change)

$$= \int_{t_i}^{t_f} C_P T_{\text{in}} \left[\left(\frac{P_{\text{out}}}{P_{\text{in}}} \right)^{\frac{\gamma-1)}{\gamma)}} - 1 \right] dm$$ (Isentropic relation)

$$\Delta E_{\text{cable}} = F \times d = \int_{V_i}^{V_f} \left(P_{\text{out}} - P_{\text{in}} \right) dV$$ (Force x Distance)

Pump work is dependent on absolute pressures, but cable work is only dependent on pressure difference.

DARTS Simulation

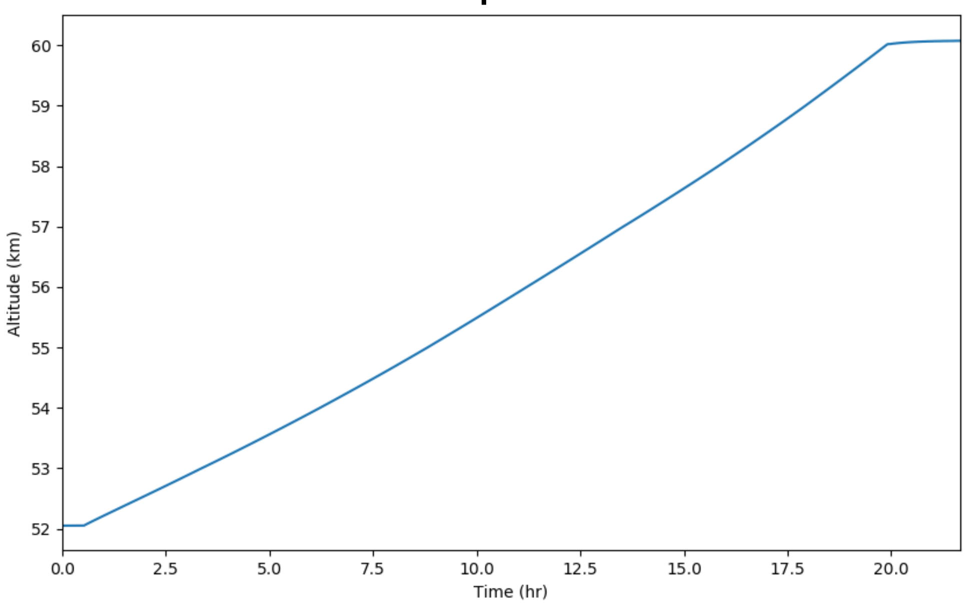


Simulation Physics – Pumped Helium Balloon on Venus

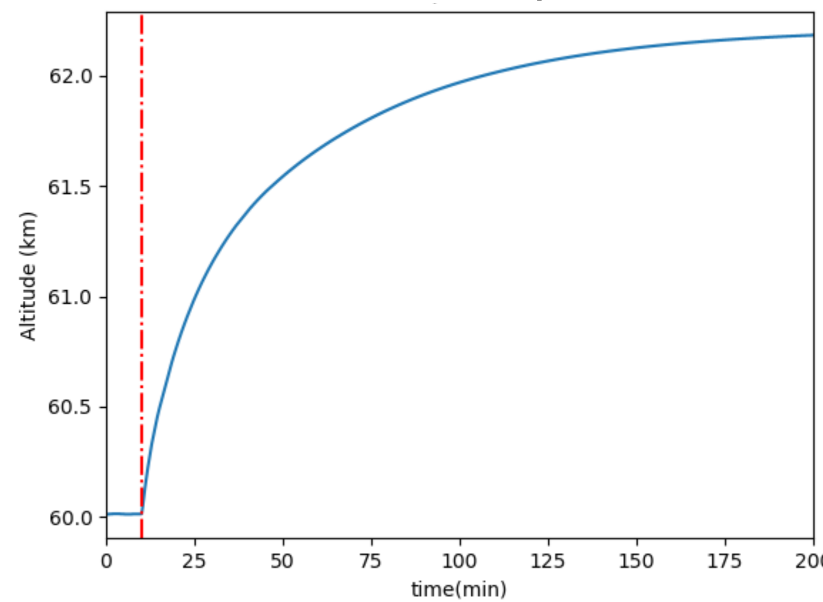
- Quadratic drag, virtual mass effects, multibody dynamics solver
- Conductive, radiative, convective heat transfers
- Validated against Carlson & Horne 1983

More Details: Jeffery L. Hall, Jonathan M. Cameron, Michael T. Pauken, Jacob S. Izraelevitz, Mitchell W. Dominguez, Kristopher T. Wehage. Altitude-Controlled Light Gas Balloons for Venus and Titan Exploration. **AIAA Aviation Forum and Exposition, June 2019**

Ascent from 52 km up to 60 km over 20 hours



3m/s Gust Response



Variable altitude balloons can now be simulated in the DARTS framework